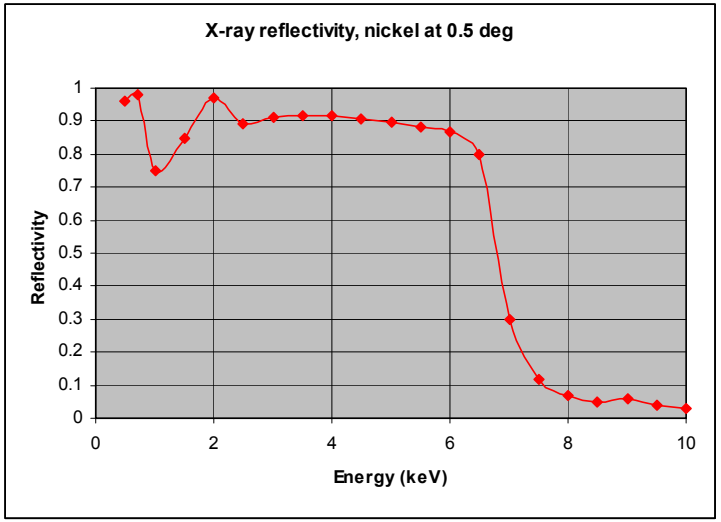
X-Ray Optics

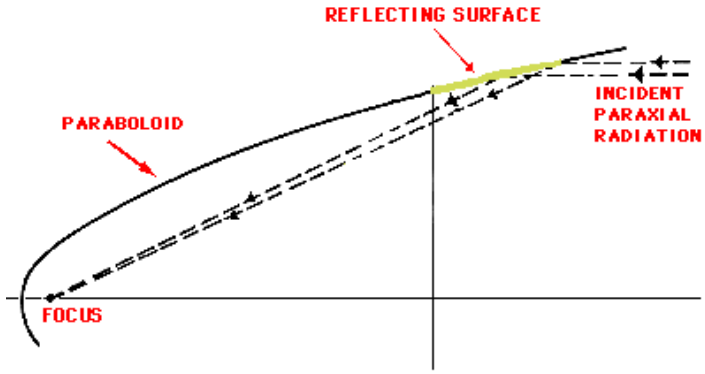
- ***X Rays undergo total external reflection at shallow graze angles***
  - ***Critical angle (away from absorption edges)***
    - > ~ θ_c (deg) = 0.93 λ (nm) $\sqrt{\rho}$ (g/cm^3)

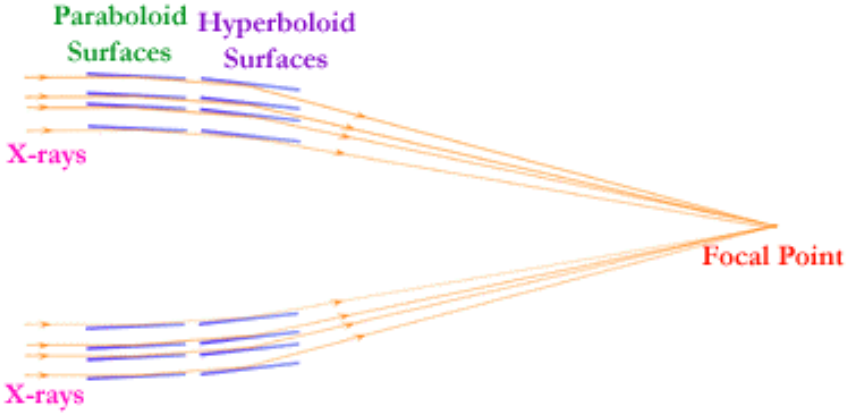
- ***Can use this phenomenon in focusing x-ray telescopes***

  Reflect x rays to a common focus

  Single parabola gives severe off-axis distortions, …
  Wolter-1 geometry adopted







X-Ray Optics

Why focus x rays ?

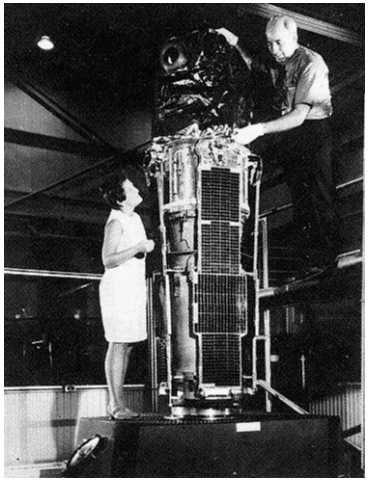
1) Imaging - obvious

2) Background reduction

- Signal from cosmic sources very faint, observed against a large background
- Background depends on size of detector and amount of sky viewed

  > Concentrate flux from small area of sky on to small detector

  ⇒ *enormous increase in sensitivity*



First dedicated x-ray astronomy satellite – UHURU →

mapped 340 sources with large area detector (no optics)

Chandra observatory - ~ same collecting area as UHURU

> 5 orders of mag more sensitivity --- 1,000 sources / sq degree in deep fields

X-Ray Optics has revolutionized (soft) x-ray astronomy

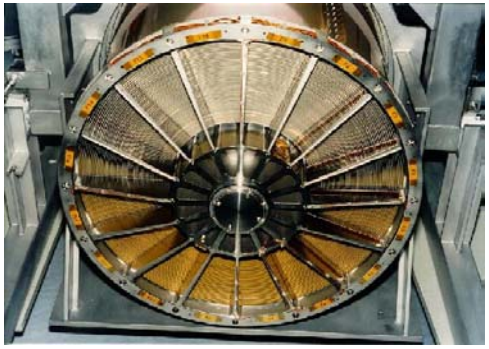
Approaches (flown so far [Soft X Ray])

Classical Optical grinding and polishing

Chandra, Rosat, Einstein

Advantage: Superb angular resolution

Disadvantage: High cost, large mass, difficult to nest

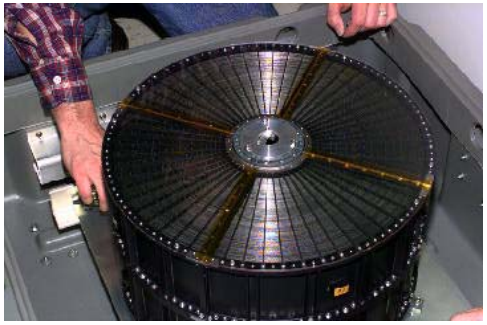


Electroformed Nickel Replication

XMM, JETX/Swift, SAX

Advantage: High nesting factor, good resolution

Disadvantage: Significant costs, significant mass (high density of nickel)



Segmented foil

ASTRO-E, ASCA, BBXRT

Advantage: Light weight, low cost

Disadvantage: Relatively poor angular resolution (arc-minute-level)

Approach adopted at MSFC

Electroform Nickel Replication (ENR)

Pioneered in Brera Observatory Italy for x-ray optics (Oberto Citterio)

~ 1992 - Work starts at MSFC -- shell for AXAF-S (45 arcsec)

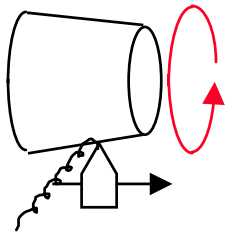
~ 1996 - 1/10-scale rehearsal mirror for AXAF-I (15 arcsec)

****

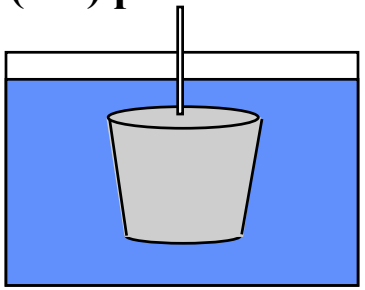
~ 1997 - two concepts, NGXO and LAXSM, combined to form Constellation-X. Work starts on ENR for the soft-x-ray telescope

Mandrel Preparation

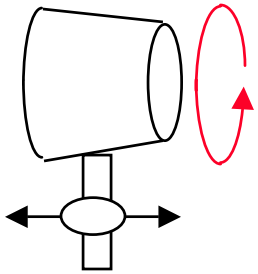
1. CNC Machine, Mandrel Formation From Al Bar



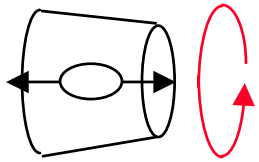
2. Chemical clean and activation & Electroless Nickel (EN) plate



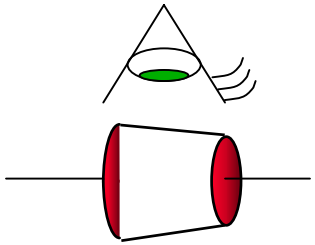
3. Precision Grind to 600Å, sub-micron figure accuracy



4. Polish and Superpolish to 3 - 4Å rms finish

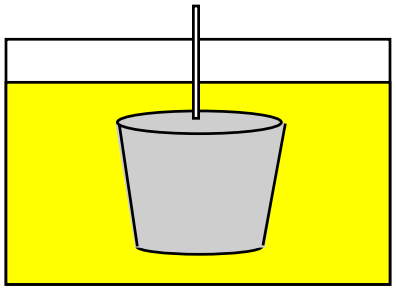


5. Metrology On Mandrel

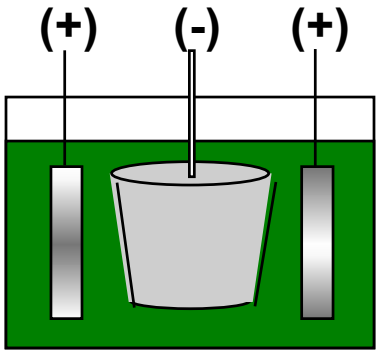


Shell Fabrication

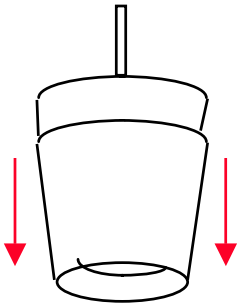
6. Ultrasonic clean and Passivation to Remove Surface Contaminants



7. Electroform Ni Shell onto Mandrel



8. Separate Optic From Mandrel in Cold Water Bath



ENR Development at MSFC

Nickel is a heavy material (9 g / cm^3). For light-weight optics, shells must be very thin (~ 0.15 mm [0.006”] at 0.5-m diameter to meet Con X SXT weight budget) yet strong enough to withstand the stresses of fabrication and subsequent handling without being permanently deformed at the micron level.

Adhesion / Release

- Reduce adhesion of plated shell to mandrel so that shell can release easily

Material Properties

- Develop nickel alloy with much higher strength than pure nickel

Stress Control

- Small amount of stress distorts thin-shell optics
  - Fine tune plating bath chemistry and keep electric fields uniform

ENR Development

- **Release Coatings**

  - Electroplating must adhere to mandrel so that shell will grow, but must be loose enough to separate easily

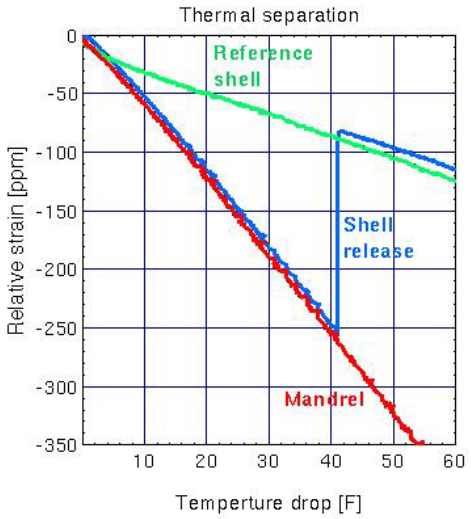
  - Have developed mandrel-surface treatments that give very low adhesion and do not significantly degrade surface with multiple replications.

  - All involve generating an oxide on the surface of the mandrel

    > Typically give ~ 7.10^5 Pa (100 psi) adhesion

      – This is a minimum to support the electroforming

ENR Development



Thin shells can experience large strain stresses under separation from a mandrel

Stress =(CTE $_{al}$-CTE$_{ni}$).Δ T.Youngs mod

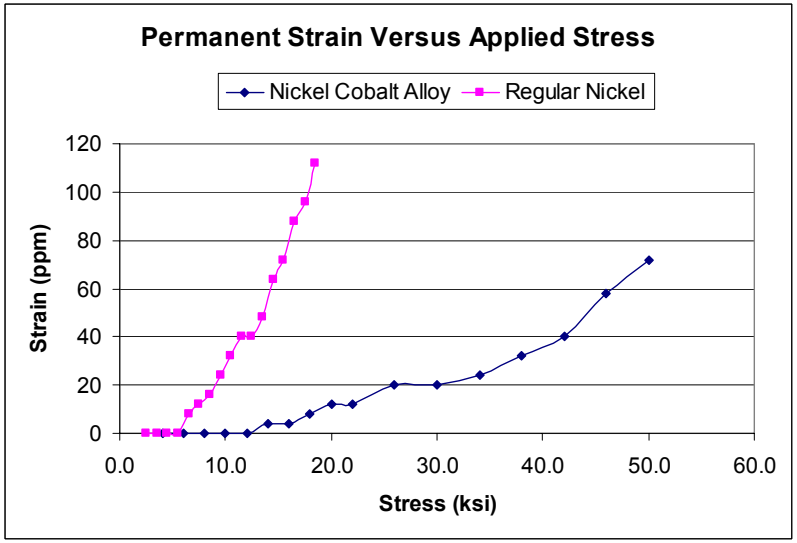
Example at right, show 0.25-mm-thick shell released from treated mandrel .. Stress ~ 35 MPa (5 ksi)

A shell 0.12-mm thick would experience twice this stress

Small stresses, well below the yield stress of a material can cause microyielding, of importance to high-resolution optics

We have developed alloys with higher yield strengths than pure nickel

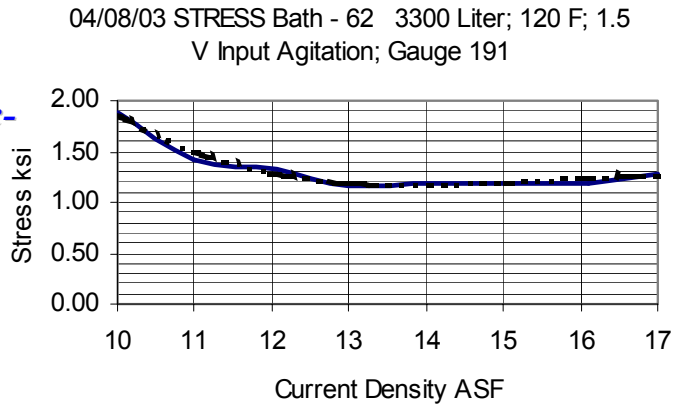
Have made shells from this alloy, just 0.075-mm-thick (0.003")



ENR Development

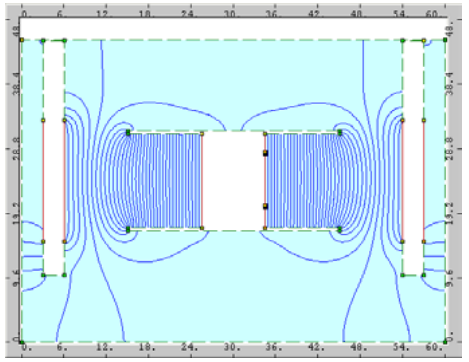
Plating stress control

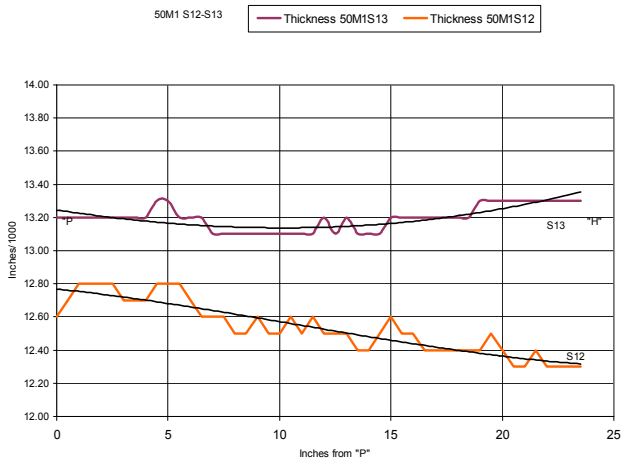
Need to control the stress to ~ 10's psi to maintain 10-arcsec-level figure ...adjust chemistry of bath to give flat uniform stress



Stress still varies with plating current density, so in turn need to control field ... use models of plating bath to fine-tune layout of shields which modify field

⇒





Resulting deposit is very uniform,

⇐

so stress variations are very low

ENR Development

Extension to Hard-X-Rays

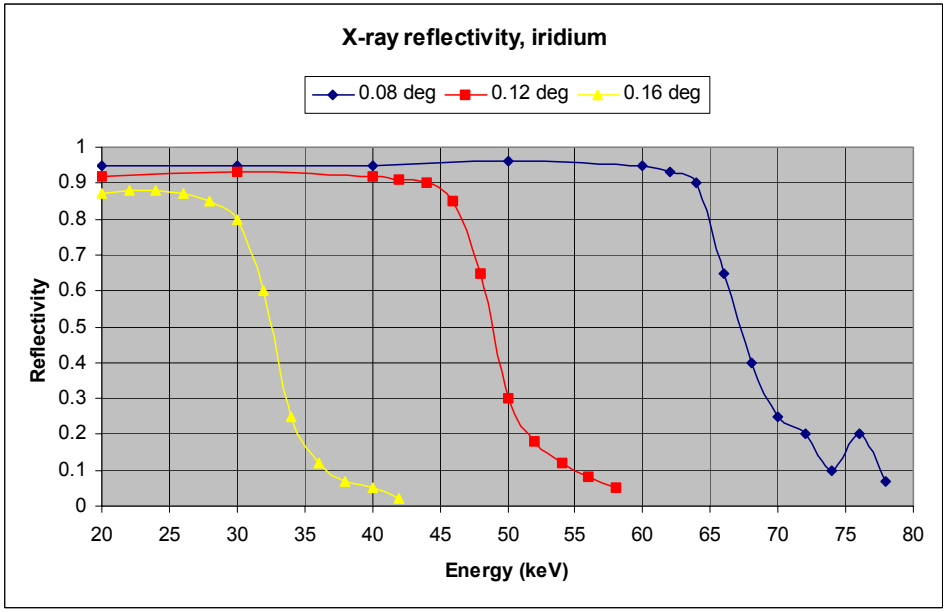
Hard-x ray is important energy region : transition between thermal and non-thermal mechanisms, nuclear lines appear, observe obscured objects + new discoveries made possible by increase in sensitivity ?

Current relatively unexplored at high sensitivities and fine angular scales (compared with lower energies)

HOW DO WE DO THIS

No magic !

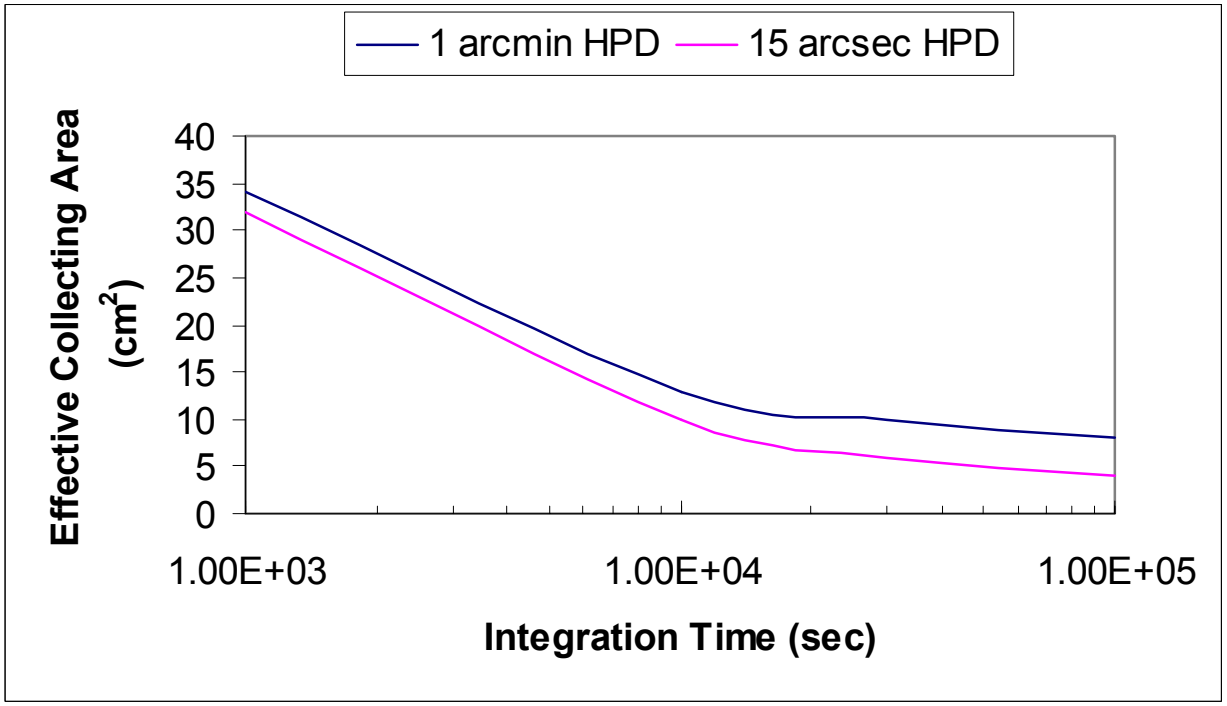
- *Long focal length*
- *Heavily nested small-diameter shells*
- *Ir coatings*
- *Multilayer coatings*



Motivation (again)

Even modest collecting areas can provide high sensitivity for pointed observations:

Figure below shows the equivalent (6m) mirror collecting area needed to equal the sensitivity of a 1000 cm^2 area coded aperture telescope for different integration times. Band is 30-50 keV, 5 sigma. Background taken as 5.10^{-4} counts / cm^2 s keV.



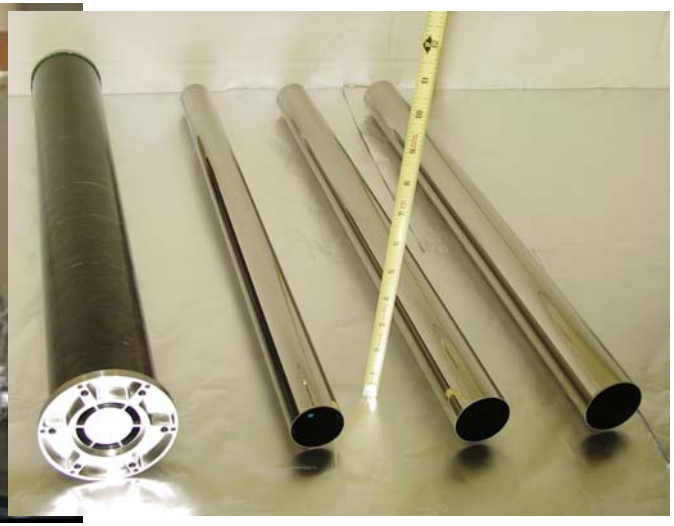
Application : HERO Program

- **HERO, for High Energy Replicated Optics, is a balloon program designed to demonstrate MSFC optics and perform science.**

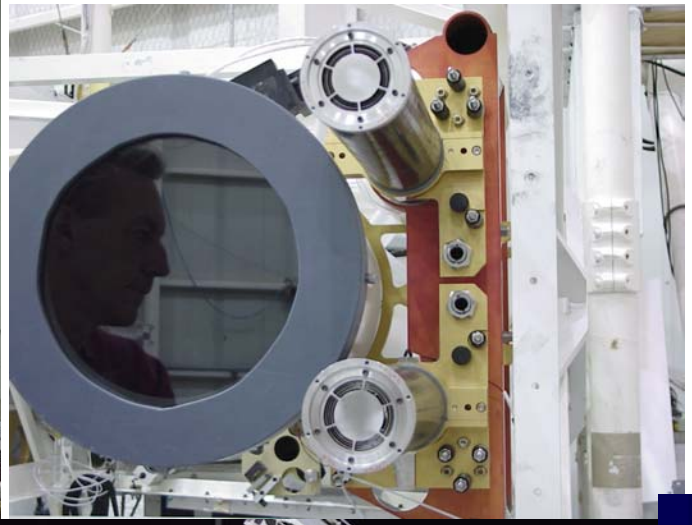
- **Utilizes in-house-fabricated hard-x-ray mirrors *plus* supporting x-ray detectors, gondola and pointing system.**

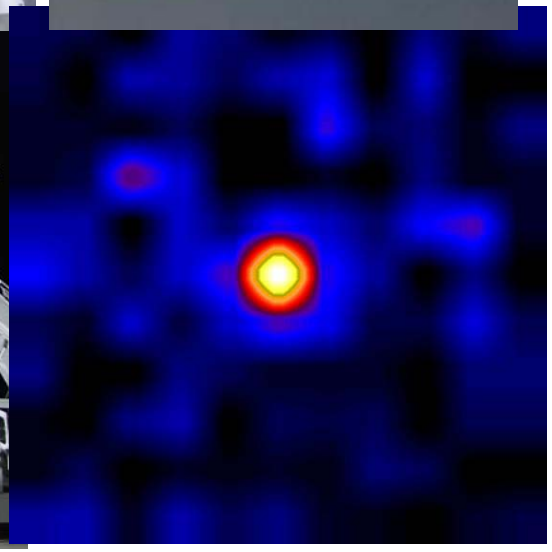
- **Optic design philosophy :**
  - Utilize a large number of shallow-graze-angle, iridium-coated full-shell mirrors
  - Obtain significant collecting area by using narrow-aspect ratio mirror shells (ie large length to diameter ratio), by nesting many thin shells and by using multiple mirror modules.
- **Cost Factor (big concern):**
  - Use conic approximation to Wolter-1 geometry
  - Keep costs down by utilizing inexpensive grinding for mandrel figuring
  - Develop simple polishing machines
  - Electroform multiple shells simultaneously

HERO Proving Flight Mirror Shell Production



HERO Gondola Assembly & Proving Flight (01)





HERO Gondola Assembly & Proving Flight (01)

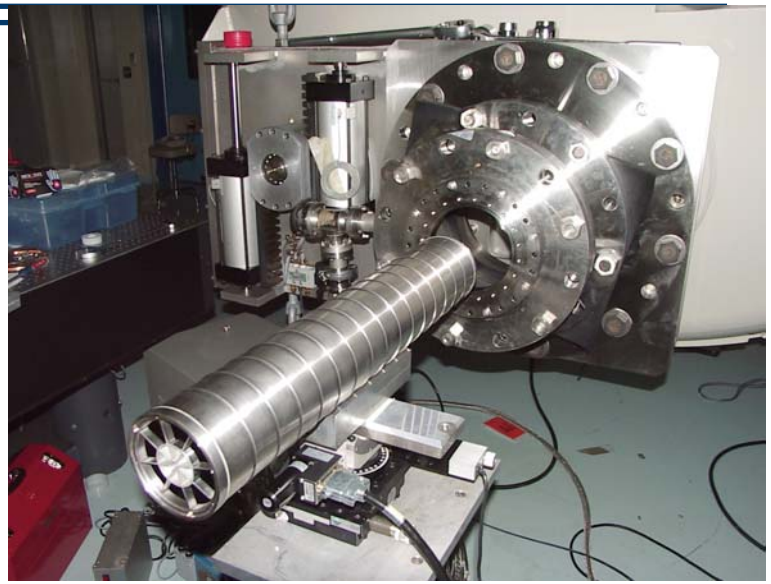
On May 21, 01, with < 4 cm^2 of collecting area (6 shells, 3-m focal length, 30-45 arcsec resolution) captured first hard-x-ray focused images of galactic sources

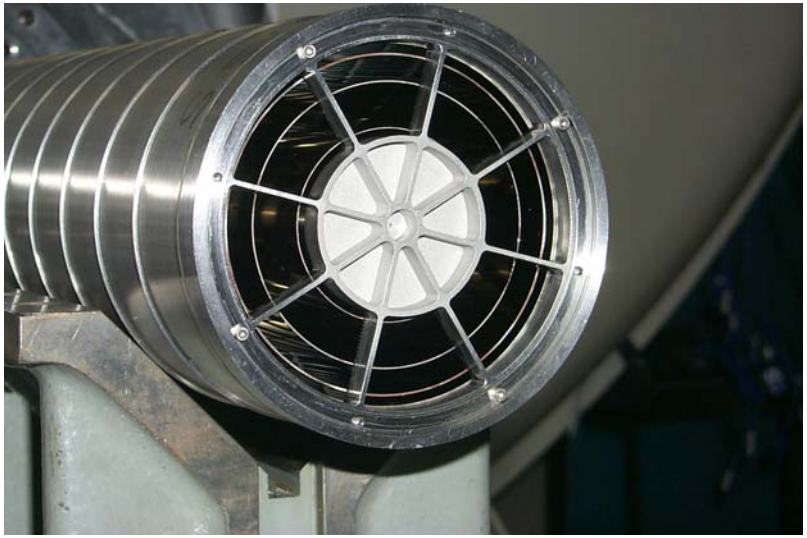
Submitted proposal to NASA SR&T program to build much bigger payload – 200 cm^2 at 50 keV – (240 shells, 6-m focal length, 15 arcsec resolution) ---- currently under development

HERO Mirror Configuration

Parameter	Value
Mirror shells per module	15
Inner shell diameter	50 mm
Outer shell diameter	94 mm
Total shell length	610 mm
Focal length	6 m
Type	Conical approximation to Wolter-1
Shell thickness	0.25 mm
Interior coating	50 nm sputtered Ir
Number of modules	16
Effective area	200 cm^2 at 40 keV
Angular resolution	15 “ HPD (goal)
Field of view	9’ at 40 keV

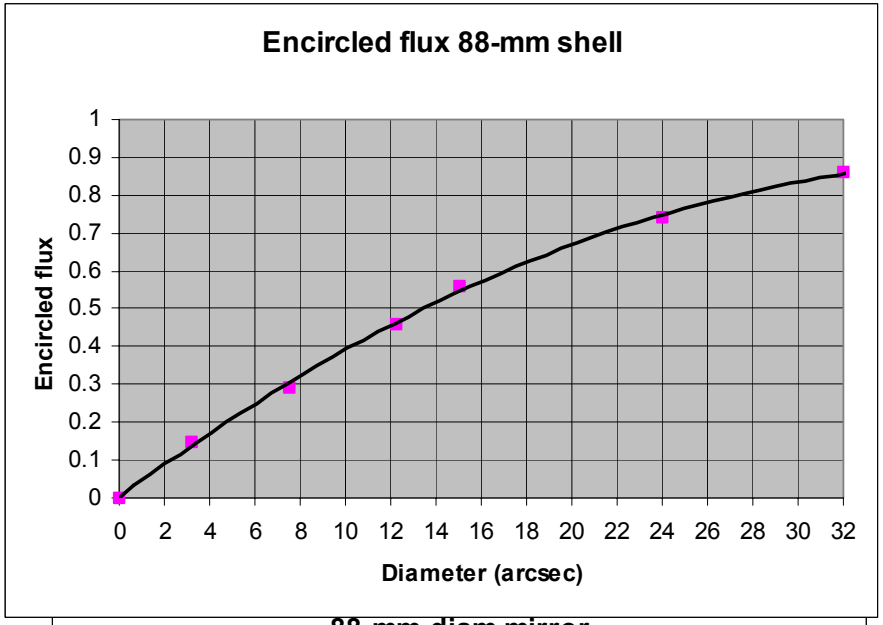
HERO Recent Mirror Fabrication and Tests

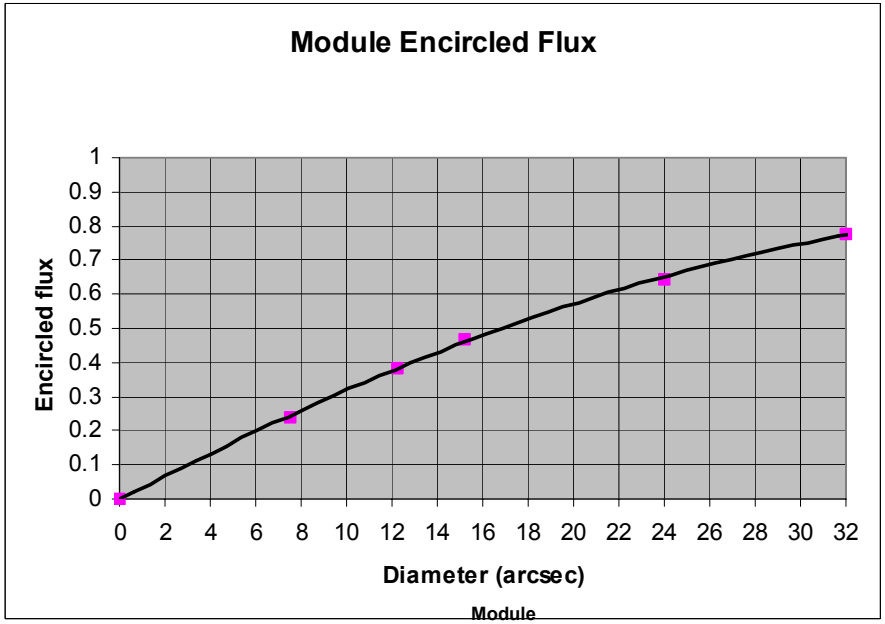


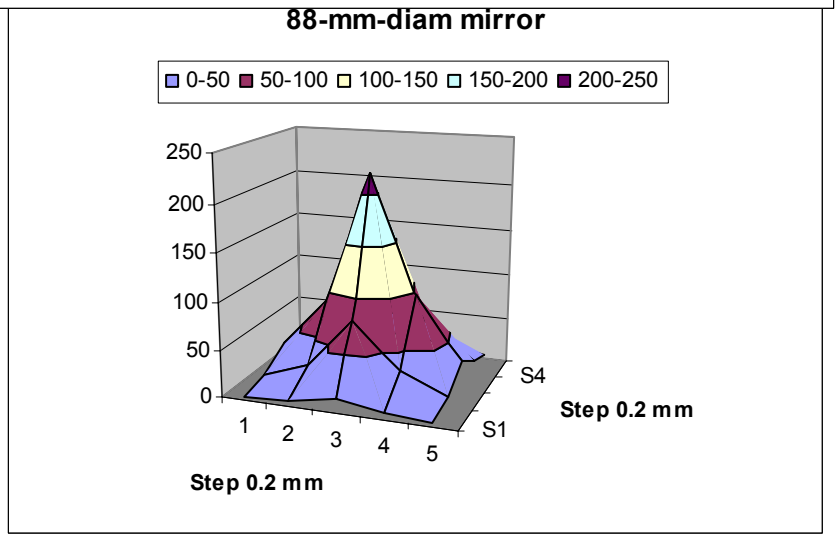


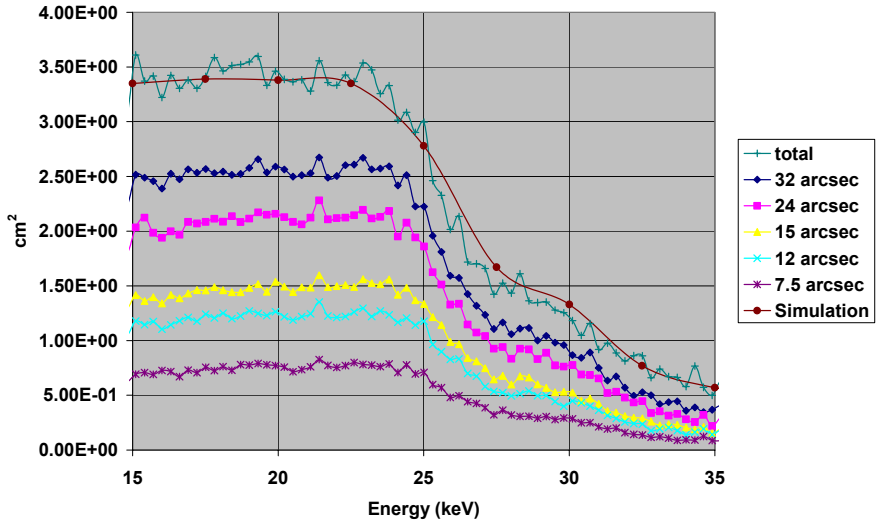
Hard-X-Ray Optics Development at MSFC

HERO Recent (Jul-03) Mirror Tests Results









HERO Test Data

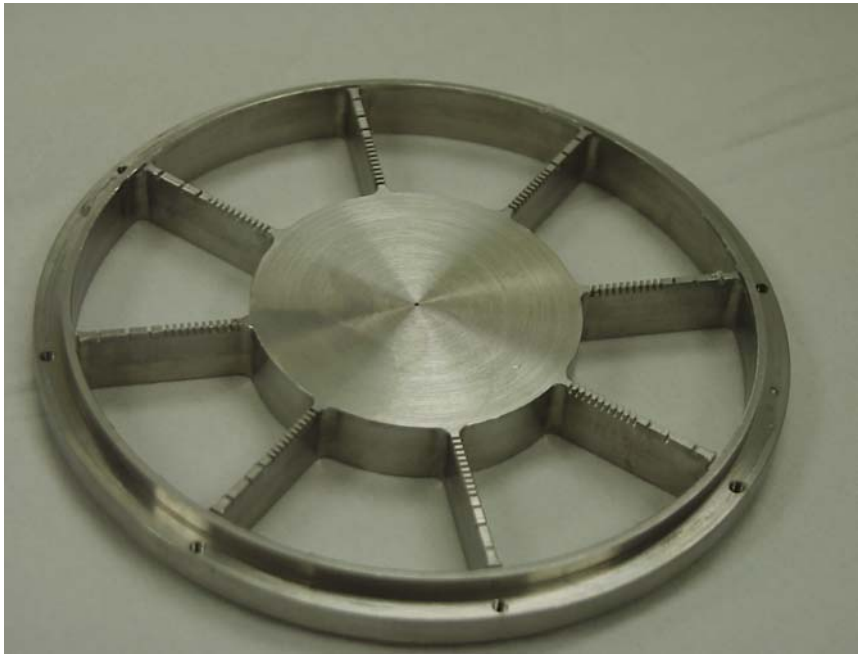
- HERO mandrel metrology gives predictions of 8-10 arcsec HPD
- Individual shells measure 13-15 arcsec HPD
- Module (4 shells) gives 17 arcsec HPD (Goal was 15 arcsec)

- *Suspect shells*

are distorted by mount

- *Plan further metrology on*

mounted shell

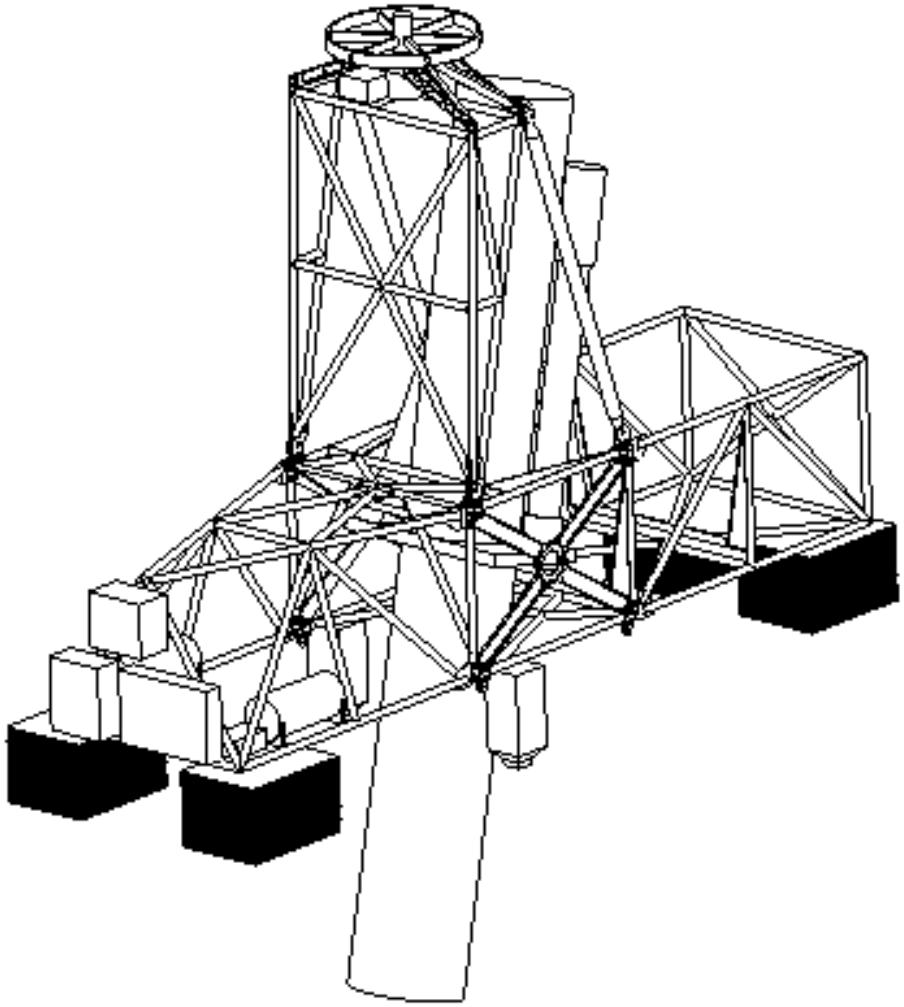


HERO Current Status

- ***Flight planned for Spring 04 from Fort Sumner, New Mexico***
  - *8 mirror modules with 8 shells each*
    - > *Total effective area = 60 cm^2 at 50 keV (1/3 of total)*
- ***Mirror Status***
  - *8 mandrels completed*
  - *44 of 64 shells completed (but can electroform 6 shells / week)*
  - *Still need to apply Ir coating*
- ***Detectors***
  - *8 (GSPC) detectors under construction*
- ***Gondola***
  - *Fabrication nearing completion (Lower section in high bay, upper section next week)*
  - *Optical bench being wound*
  - *Electronics near completion*

HERO

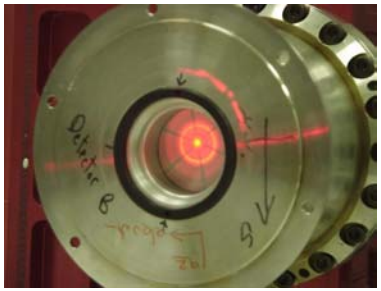
HORIZONTAL GONDOLA LAYOUT



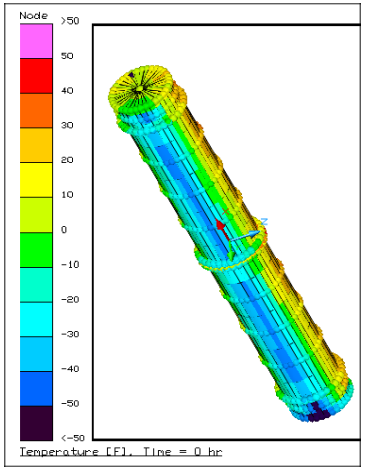
Optical Bench Deployed

HERO Current Status

- ***Some challenges flying 15 arcsec optics on a balloon***
  - *Alignment*
    - *> Laser alignment system to co-align mirror modules to star camera*

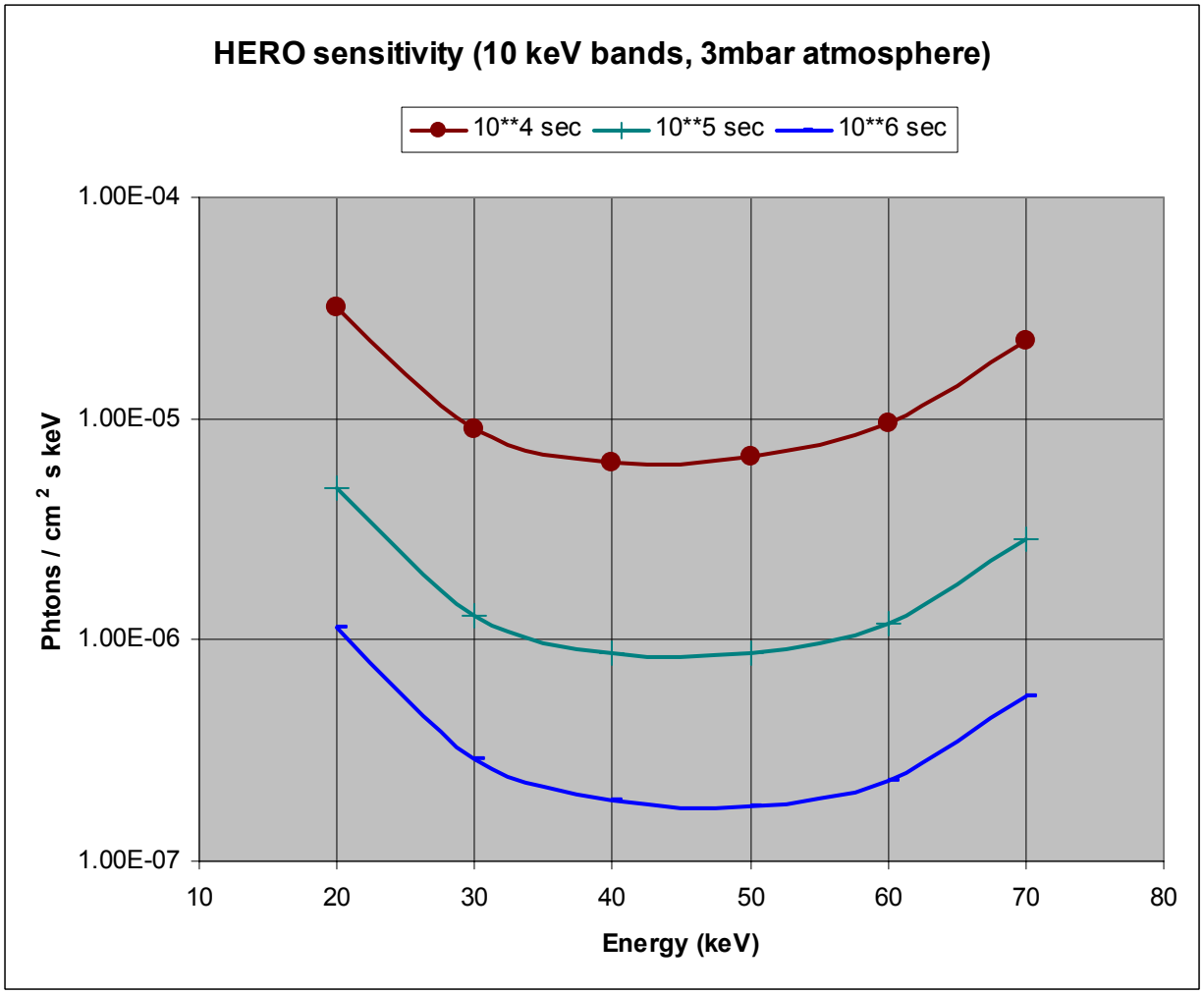


  - *Stability*
    - *> Extensive thermal modeling necessary (+20 → -70 ºC environment) for optical bench to optimize composite weave (SD22+ED26)*



  - *Pointing / aspect*
    - *> Normal sun sensors / magnetometers not good enough*
      - *– Developed day/night aspect camera (9-10 th mag during day / < 8 arcsec)*

HERO 5-σ Sensitivities (16 Mirror Modules)



HERO targets ?

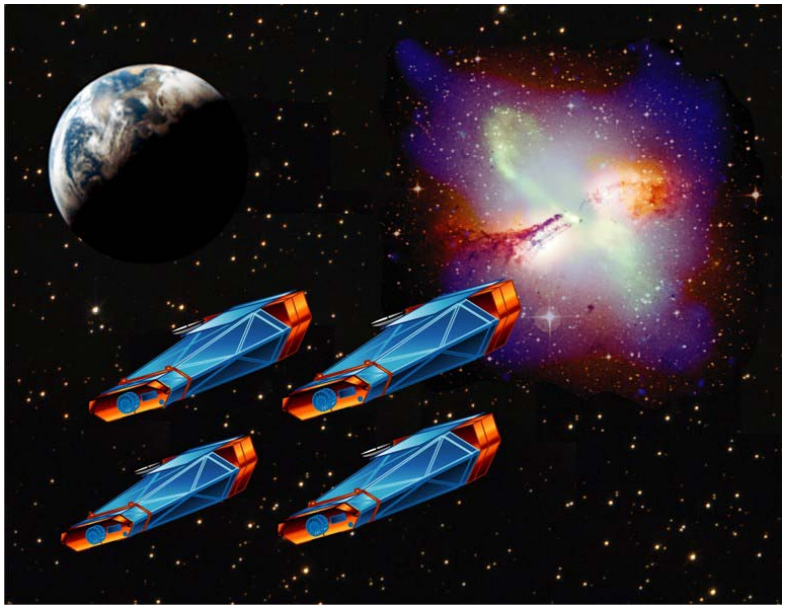
Areas of interest include:

- Cyclotron lines –*Measure field and get information on accretion flow*
- Hard-x-ray tails in black hole candidates -- *Look for distinctive hard-x-ray characteristics*
- ^{44}Ti lines in supernova remnants -- *Tests of nucleosynthesis and dynamics of ejecta*
- Clusters of galaxies –*Measure emission from point sources and intracluster gas*
- Obscured AGN – *Measure Compton reflection component*

Application - Constellation-X

Baseline Mission Characteristics

Minimum effective area:	1,000 cm^2 from 0.25 keV to 10 keV 15,000 cm^2 at 1.25 keV 6,000 cm^2 at 6.0 keV 1,500 cm^2 from 10 keV to 40 keV
Minimum telescope angular resolution:	15 arcsec HPD from 0.25 to 10 keV 1 arcmin HPD from 10 keV to 40 keV
Spectral resolving power: (E/ΔE)	>~ 300 from 0.25 keV to 6.0 keV 1,500 from 6.0 keV to 10 keV > 10 from 10 keV to 40 keV
Band Pass:	0.25 to > 40 keV
Diameter Field of View:	SXT > 2.5 arc min > 30 x 30 array (5'' pixels) HXT > 8 arc min
Mission Life:	> 4 years (full capability)
Redundancy/Reliability:	No one on-orbit failure to result in loss of more than 25% of the mission science



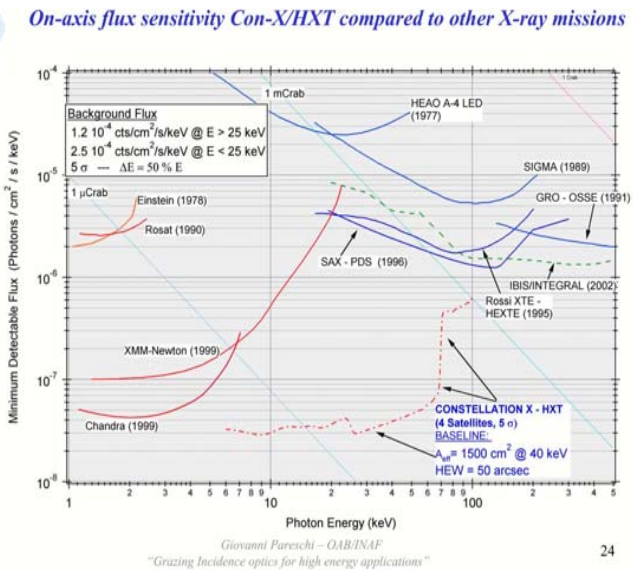
http://constellation.gsfc.nasa.gov/docs/science/staudience.html

Constellation-X

To meet HXT baseline requirements need the following optics configuration:

- *3 mirror modules per satellite*
- *~ 85 nested shells per module*
- *Inner shell ~ 100 mm diameter*
- *Outer shell ~ 330 mm diameter*
- *Total shell length ~ 70 cm*
- *Focal length = 10 m*

~ Depends on technology used



Constellation-X

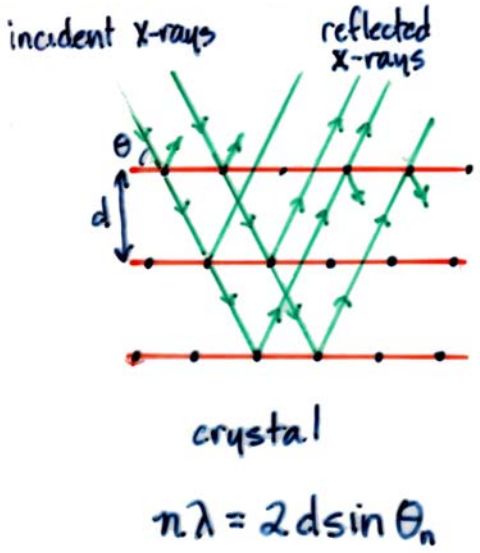
HXT optics will have multilayer coatings:

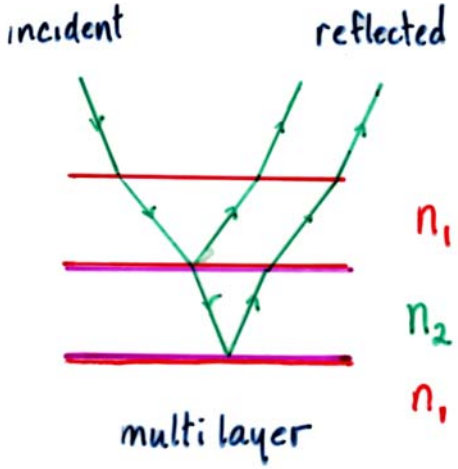
Graded multilayers operate on the principle of Bragg reflection

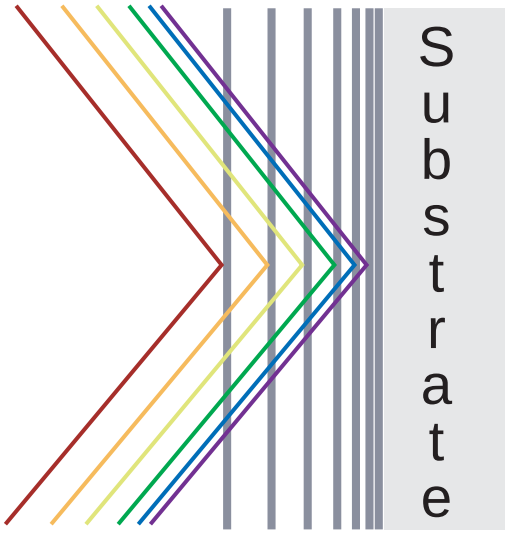
alternating layers of low and high index of refraction

$n\lambda = 2d \sin\theta$ – d = bilayer thickness

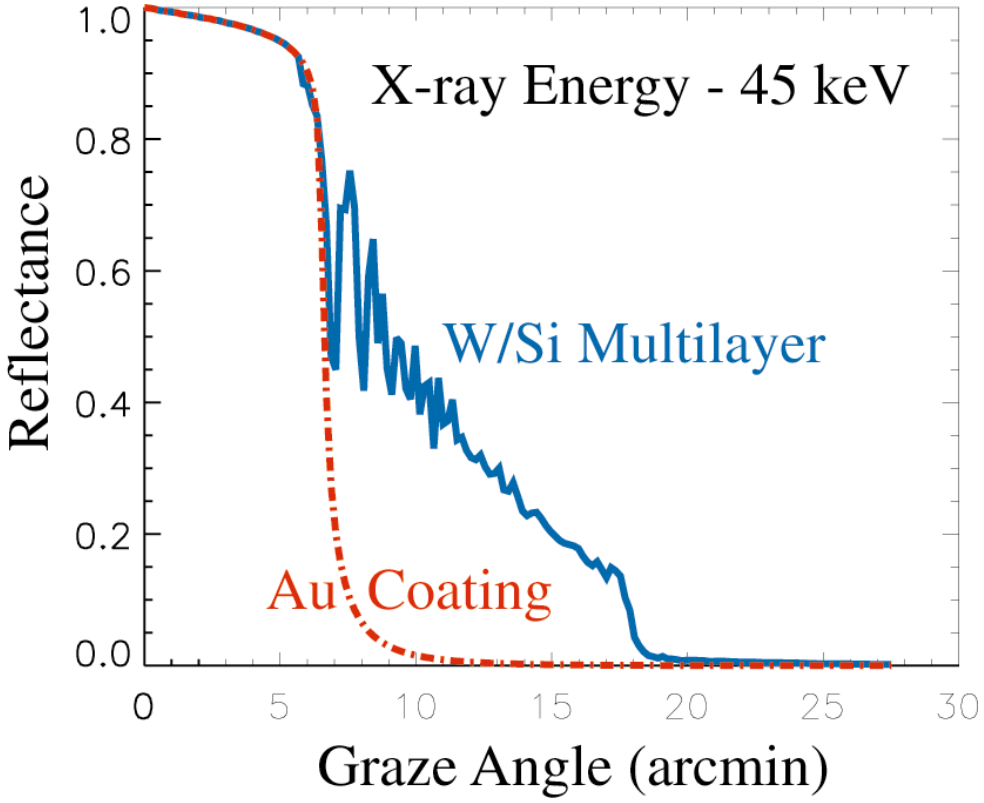
Wide range of bilayer thickness provides broadband reflectance

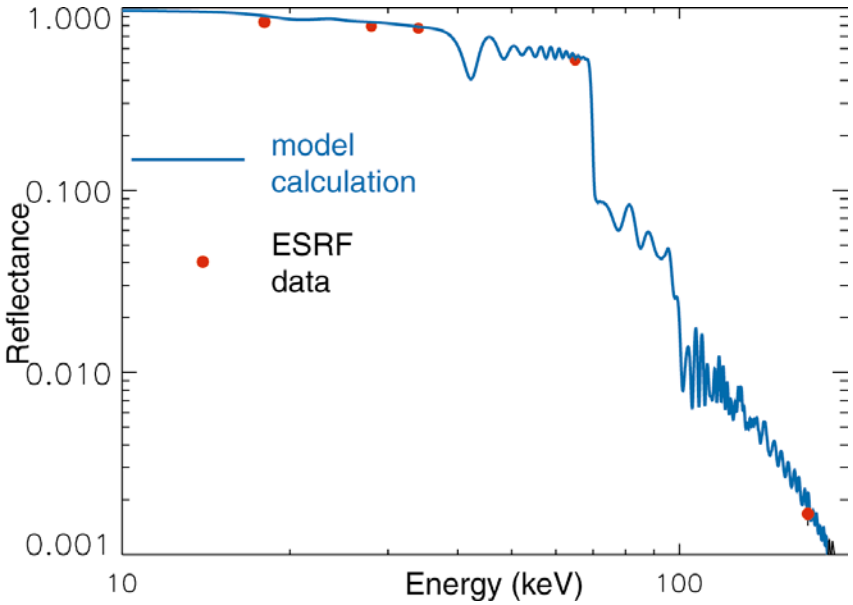






Constellation-X





ESRF synchrotron measurements of HEFT D3 (7.5 arcmin) W/Si multilayer, 250 bilayers

Constellation-X

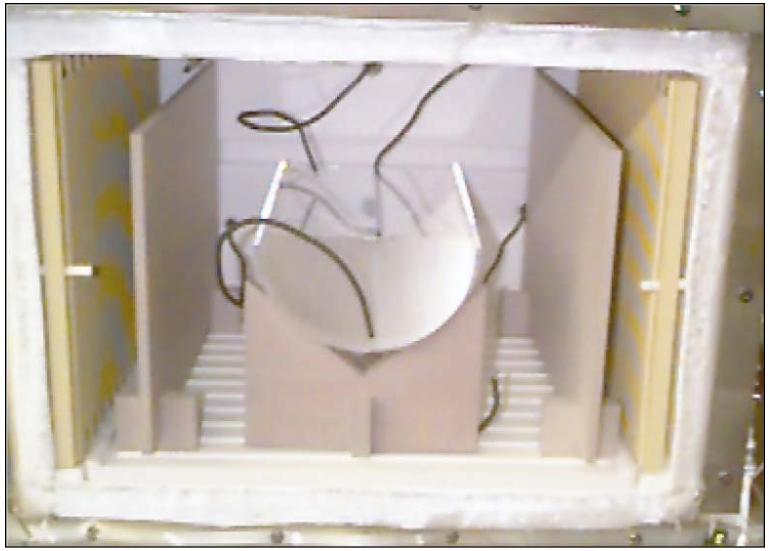
Two competing technologies are being evaluated :

1) Electroformed nickel full-shell optics

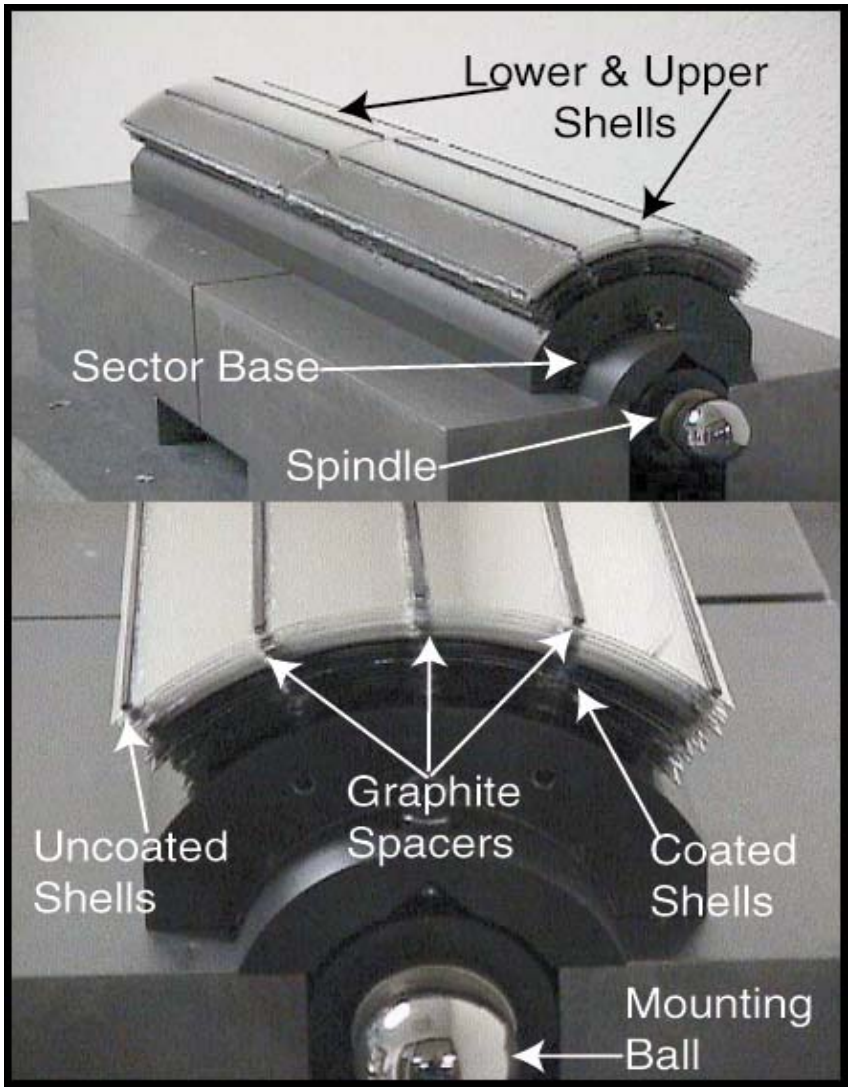
Good angular resolution (√) Heavy material = very thin shells (X)

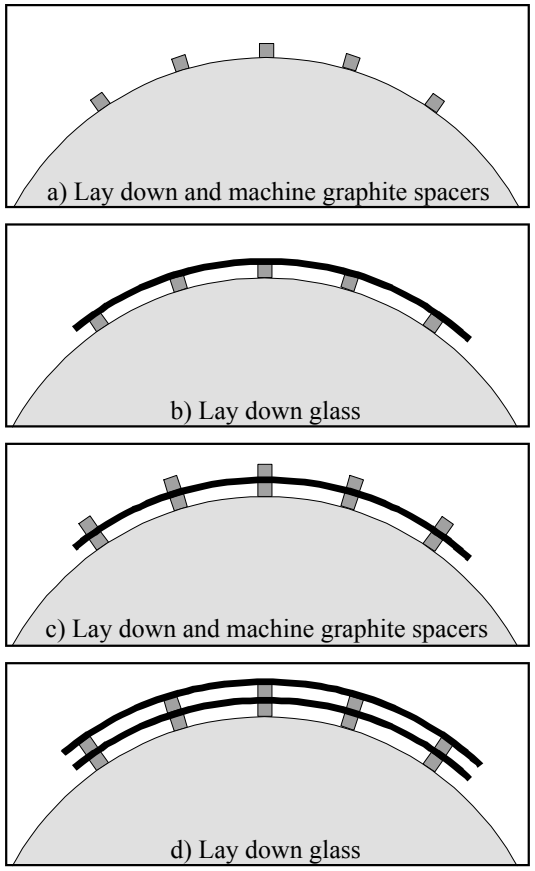
2) Slumped glass segmented optics

Light material (3 X lighter than nickel)(√) Difficult to achieve good angular resolution (X)



Constellation-X





Constellation-X

- **A prototype HXT optic will be made using each technology**

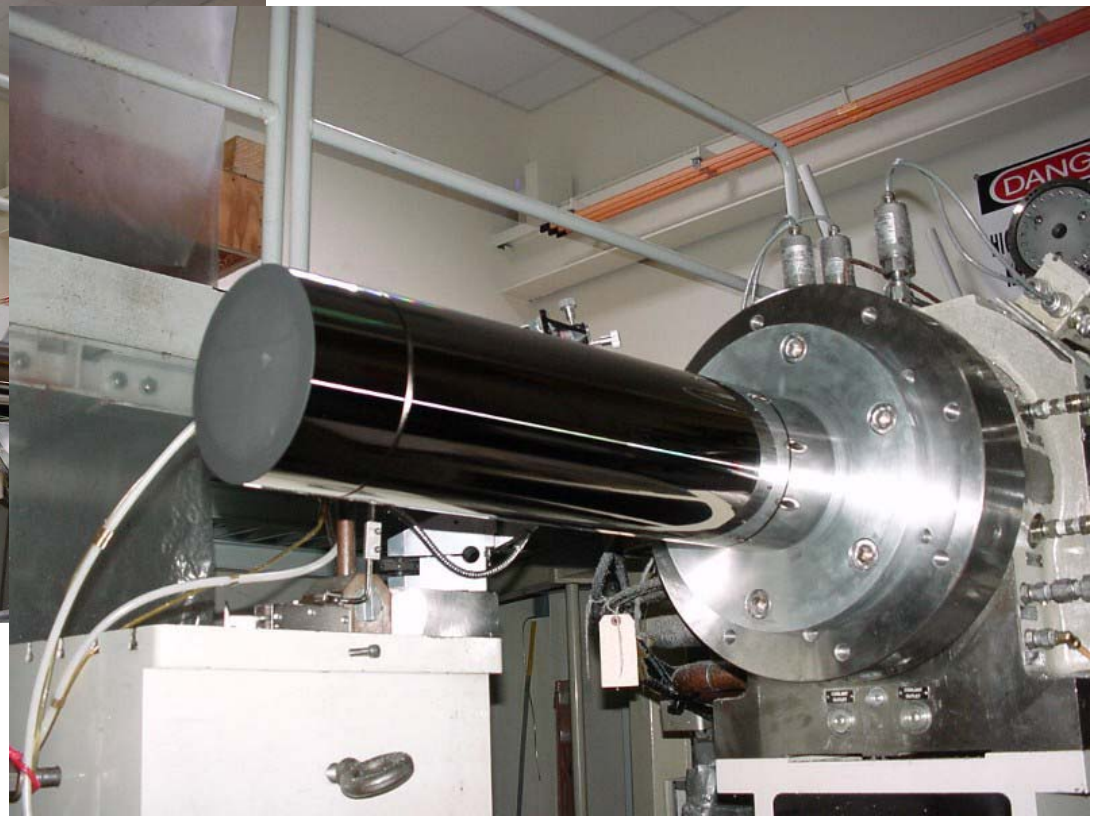
- **MSFC is collaborating (with Brera Observatory, Italy and SAO) on the nickel full shell version**

  - MSFC will produce two shells
    - > 426-mm-long, 230-mm diameter shell to be coated with multilayers (SAO)
    - > 426-mm-long, 150-mm diameter shell to be coated with Ir
  - Both shells need to be 100 micron thick to meet HXT weight budget
  - Larger shell must have very good surface finish for multilayer coatings (< 5Å RMS)

Constellation-X

- 150-mm-diameter mandrel after NiP coating (before diamond turning)

Constellation-X



Constellation-X

- **Mandrel Production (23 cm)**

Wyko data:

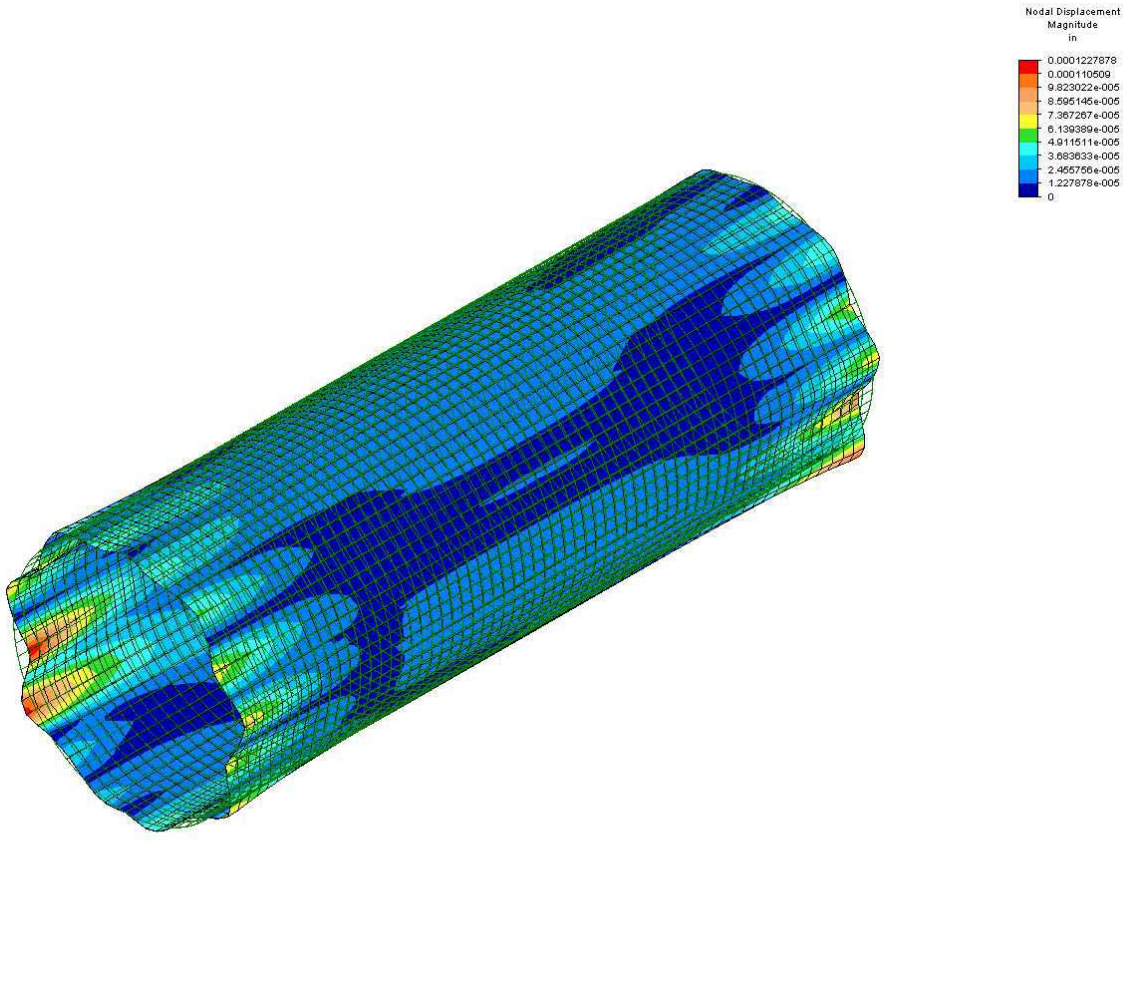
'P' end : 2.8 A RMS

'H' end : 2.6 A RMS

Figure : About +/- 0.1 micron

Prediction : 10 arcsec HPD

Constellation-X



Constellation-X

- **Mirror Surface Concerns**

  - Multilayer coatings require an extremely good surface, far better than Ir-coated optics (e.g. HERO)
    - > **As thinnest multilayers layers are ~ 20 A, surface needs to be better than ~ 5 A on all scales (need AFM measurements of substrates)**
      - – **But, thin shells need to easily separate with minimum adhesion**
        - » **Challenge is to find the right surface treatment to achieve this**

  - Our standard separation process gives < 2-3 A on WYKO (optical) , but ~ 10 A on AFM . This means that most of the microroughness is below micron.

  - We are currently evaluating other separation processes (some that we used several years ago)

Constellation-X

- **Stress Concerns**

  - Stress in the multilayer coatings is a concern as it could alter the figure of the very thin optic

  - Stress can be inherent in the coatings, or can come about due to heating during the coating process. On cooling, the different CTEs of the coating materials and the nickel shell, give rise to a stressed system.

  - We have modeled this effect for a shell the size of the prototype optic (20 cm diameter, 42.6 cm long and made of 100-micron-thick nickel. The modeled coating is 1 micron thick.

Constellation-X

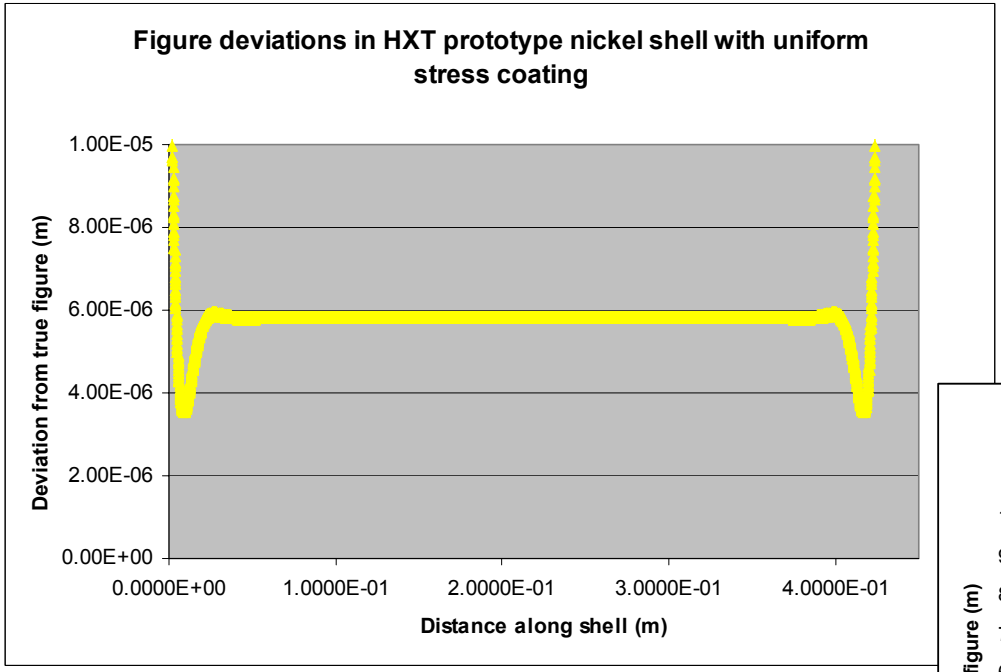
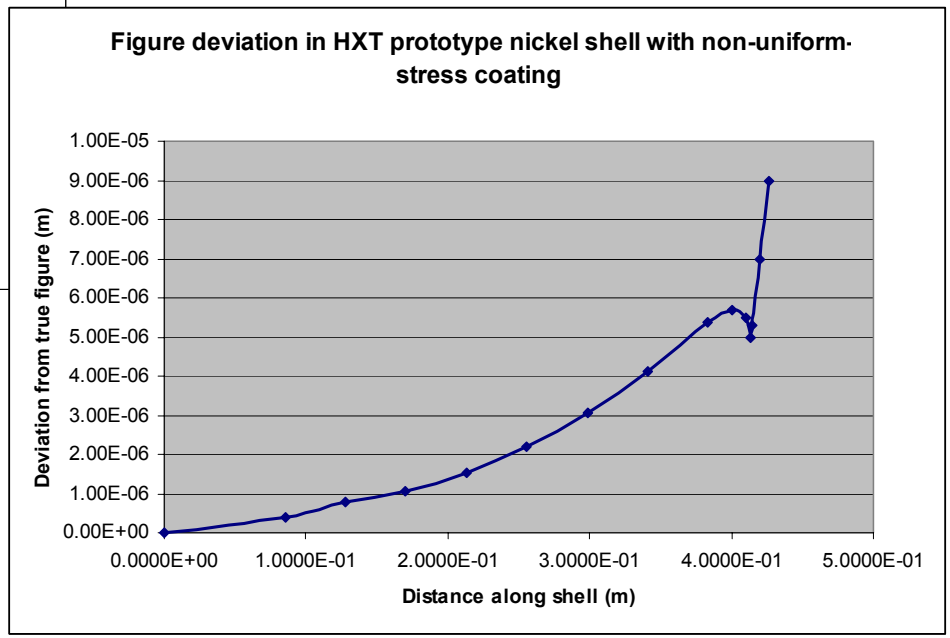


Figure on left shows effect of uniform stress (170 MPa, 25 ksi) in multilayer coating. Shell degrades to 11 arcsec from 10 arcsec

Figure on right shows the effect of non-unifom stress 20 MPa to 170 MPa along the shell length. This figure gives a 22 arcsec optic. Stress variation is equivalent to a 40 °C differential.

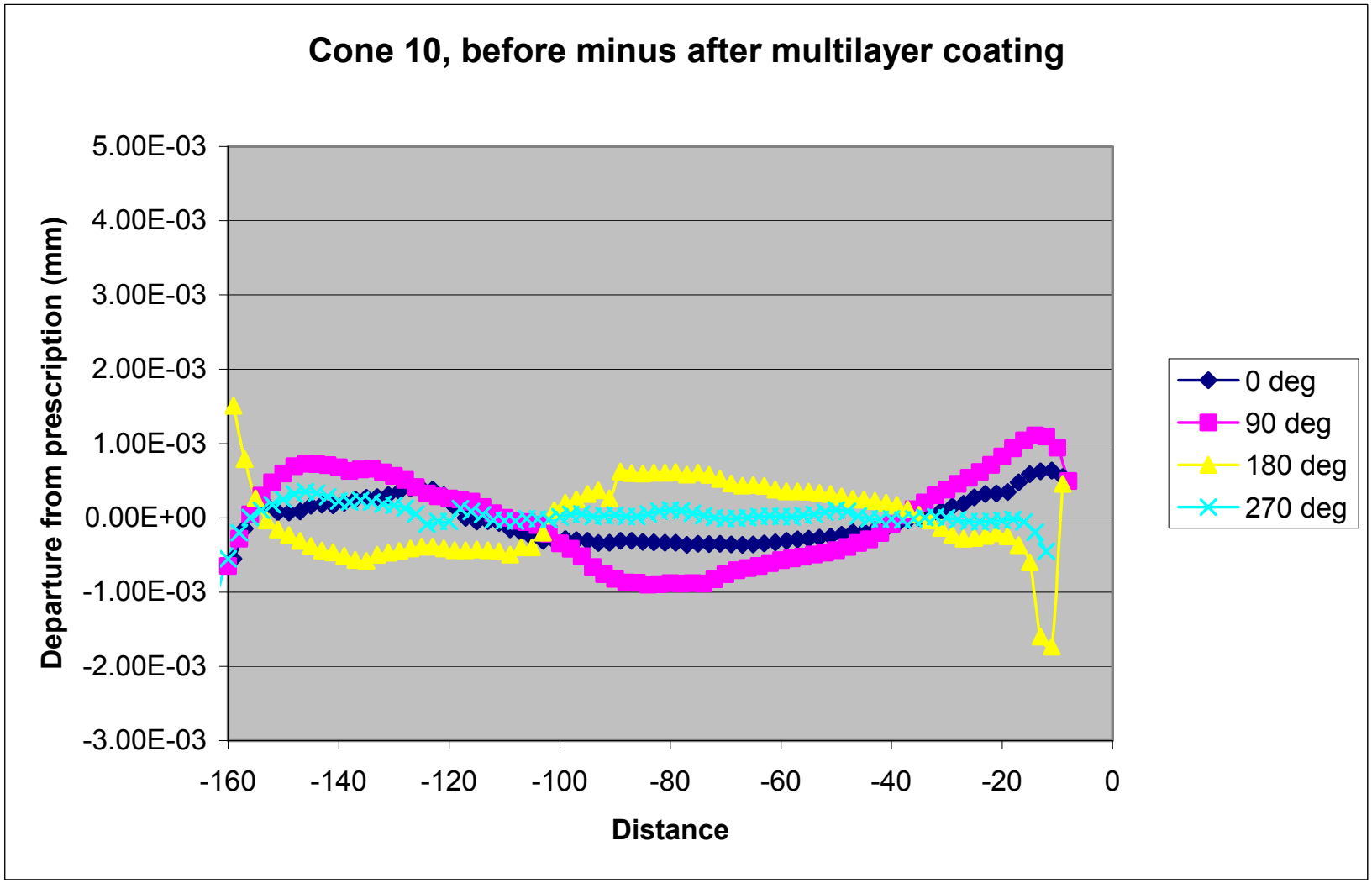


Constellation-X

- *Series of small cone shells, 23-cm diameter, 20-cm long, 100 micron thick, fabricated for multilayer stress tests from earlier lower-surface-quality mandrel*

1. *Measured at MSFC*
2. *Coated with 1 – 1.5 micron of W/Si multilayers at SAO*
3. *Returned to MSFC for final metrology*

Constellation-X



Constellation-X

- **Status**
  - Shells to Brera for integration (Early 04)
  - Testing at MSFC (Late 04)
  - Decisions ?

Future Developments

- **Reduce mass of plated deposit**

  - Nickel is 8.9 g / cm^3 (3 x density of glass) - large number of shells are needed to give desired collecting areas ⇒ very thin shells necessary to meet tight weight budgets.

    > *Investigate electrocomposites*

- **Improve angular resolution**

  - Current optics are limited by axial figure errors due to stress variations in plating

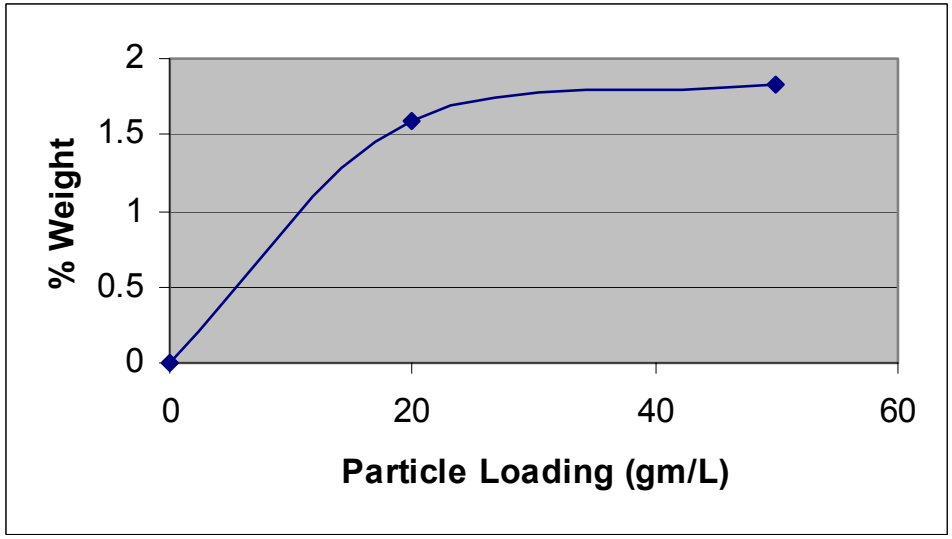
    > *Investigate thermal setting*

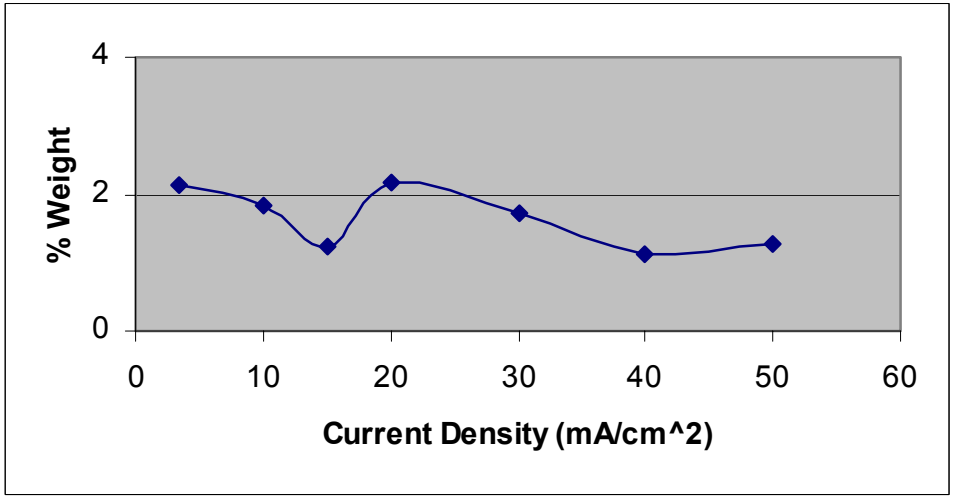
Future Developments

- **Electrocomposites**
  - Materials added to the plating bath become incorporated in the nickel deposit
    - > If additives are light-weight and have a high modules, then can end up with a lighter,stronger composite material
      - – This work was started several years ago, but put to one side when high-strength alloys nickel were developed.
      - – Re-visited last summer for us by Pei Xiong-Skiba, summer faculty (Austin Peay State University, Clarksville, Tn)

Future Developments

- **Electrocomposites**
  - Used alumina particles, 50 nm size, in plating bath. Experimented with various concentrations and various standard plating conditions:





Results were disappointing, as could only get a small decrease in plated deposit density … to 8.6 g / cm^3

Future Developments

- **Electrocomposites**
  - Switched to pulse plating … plate for period of time then etch back the deposit
    - > Achieve much more encouraging results
    - >

Sample #	J_+ (mA/cm^2)	t_+ (ms)	J_- (mA/cm^2)	t_- (ms)	J_{ave} (mA/cm^2)	ρ_{com} (gm/cm^3)	% Wt	n (1/cm^3)	Duty Cycle
25	20		0	0,000	20.0	8.7573	1.4	4.9×10^{13}	1.0
22*	20	15,000	-40	3,000	10.0	7.9007	7.5	3.4×10^{14}	0.6
23*	20	23,000	-40	7,000	6.00	7.0307	16	6.4×10^{14}	0.39
24*	20	29,000	-40	10,000	4.62	6.4817	22	8.3×10^{14}	0.31
26*	20	37,000	-40	14,000	3.53	6.7213	19	7.4×10^{14}	0.24

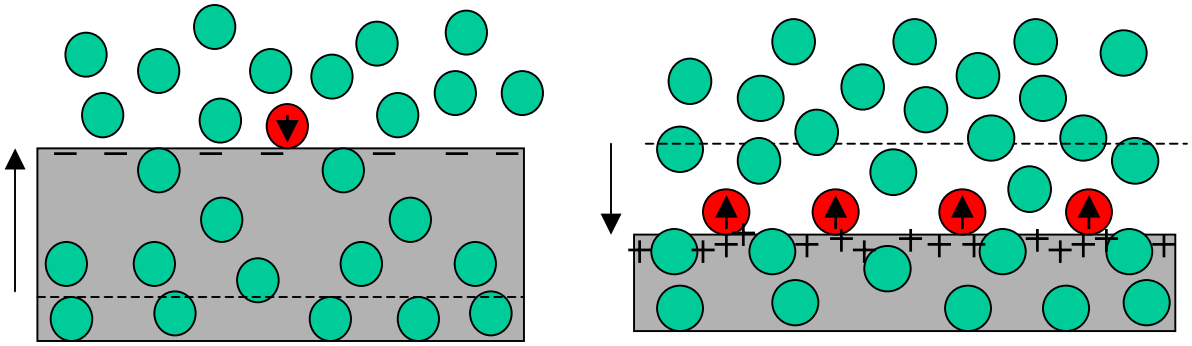


Figure 3 Model for reverse pulsing plating (plate 3D and strip 2D). The left figure shows that particles are integrated into the composite during 3D plating cycle. The right figure shows how the "released" particles remain to be attached to the surface of the composite during the 2D stripping cycle, possibly caused by the interaction between the polarized alumina particles and the substrate. Most of these particles in contact with the surface are re-trapped during the following plating cycle.

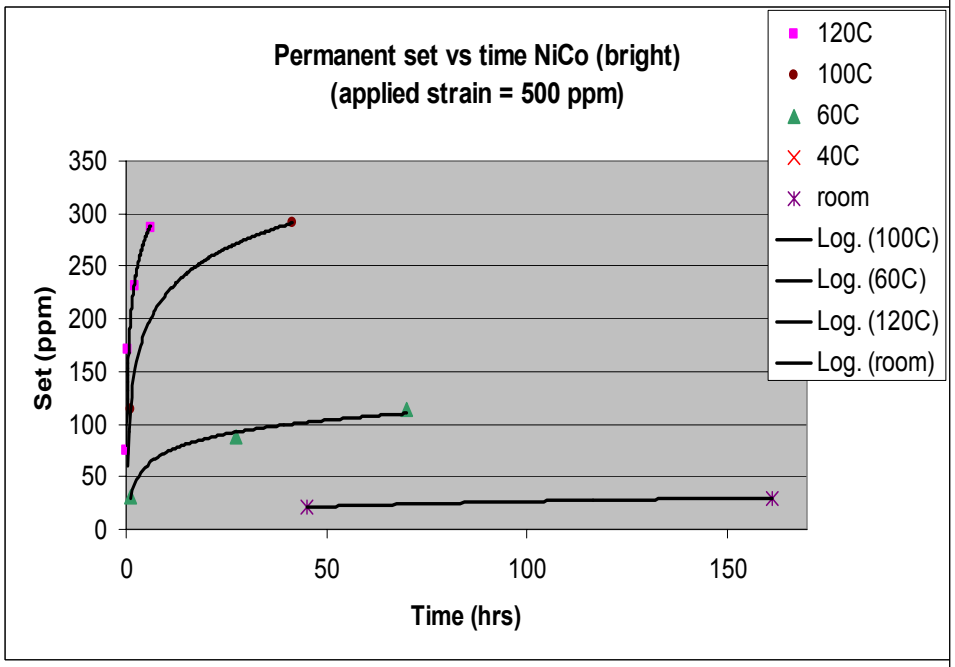
Future Developments

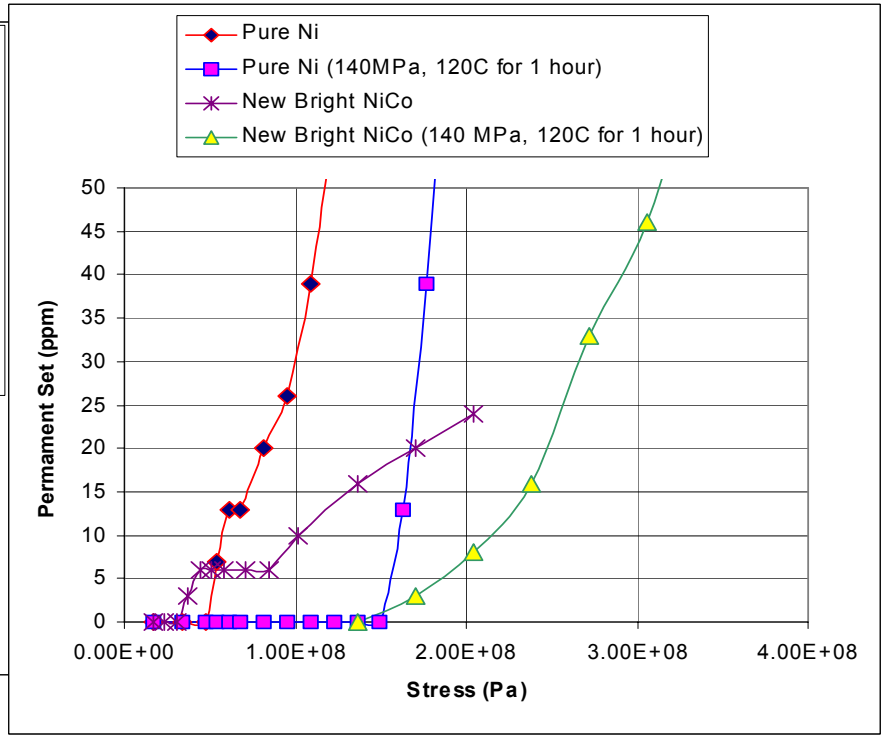
- **Electrocomposites**
  - At 6.4 g / cm^3, nearly 50% of the volume is taken up by the alumina (~ 3 g / cm^3)
  - Limit of this is uncertain…clearly some metal must be present to bind matrix
  - However :
    - > lighter additives could be used (carbon ?)
    - > Nickel phosphorous could be used in place of nickel, nickel /cobalt. NiP is only 7.9 g / cm3 to start with.

Note that as the stiffness of a shell goes with the thickness cubed, a shell with density 6.4 g / cm^3 would be nearly 3 times stiffer than the equivalent mass shell of density 8.9 g / cm^3.

Future Developments

- **Thermal Setting**
  - Noticed that some plated material that we had crammed into a (too small) oven took on the shape of the interior at a surprisingly low temperature (120 ºC.)
  - Performed series of tests on samples to examine this effect :





Future Developments

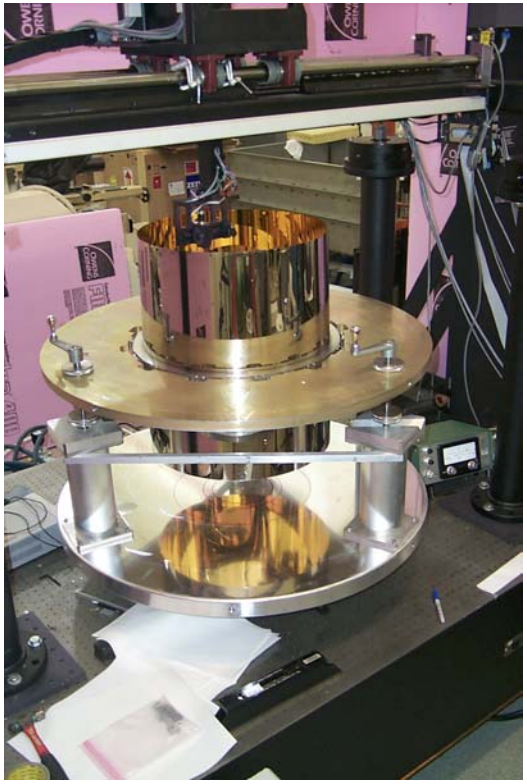
- **Thermal Setting**
  - Large amount of 'stretch' possible offers the possibility of forcing the shell to accurately conform to the mandrel
    - > Stretching also makes the material stronger (strain hardening)

What about plating stresses ?

• Evidence is that they anneal out with temp / time

• A 75 arcsec 0.5-m-diameter shell was placed back on its mandrel and heated to 120 ºC for 12 hours. After cooling and removal it now had a 15 arcsec figure (mandrel was 13 arcsec HPD)

• Shell shown at left (0.5-m-diam, 0.15-mm-thick) improved from 38 arcsec to 19 arcsec over a period of 1 year at room temp !



Future Developments

- **Themal Setting**
  - Challenge is to understand and optimize this process
    - > Early attempts placed shells back on mandrels after metrology. Difficult to do, can get them misaligned
      - – Plan series of tests with well-mapped mandrel comparing shells thermally set before removal
        - » Initially on low-quality mandrel to compare figures. Then on higher quality mandrels.

Con-X 15 cm mandrel should be ~ 5 arcsec (HPD). …possibly fabricated higher quality mandrel with Wolter-1 figure for demonstration ?

Conclusion

- ***Developed ENR process to produce thin hard-x-ray mirror shells of moderate resolution (10-15 arcsec)***
  - *This is superior to competing technology*

- ***Are using this technology to fabricate shells for the HERO balloon program and for possible use on Constellation-X***

- ***Are pursuing new developments aimed at pushing the mass down and improving the mirror resolution***